

# **Elements of a Feature-based Ultrasonic Inspection System**

by J. L. Rose

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## Abstract

*Aspects of a feature-based ultrasonic inspection philosophy are outlined in this paper. Reflector classification analysis is discussed along with the methodologies associated with physical model development, feature definitions and selection, pattern recognition, and the steps necessary from problem definition to field implementation.*

*Four sample problems that make use of the feature-based concept are reviewed in the paper. They include adhesive bond inspection, weld inspection, stainless steel piping inspection, and breast tissue classification.*



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## INTRODUCTION

Ultrasonic inspectors can usually carry out defect presence and location analysis very precisely. Unfortunately, the state of the art is such today that they cannot tell very much about the characteristics of the reflector. The purpose of this paper is to review the development of concepts from signal processing and pattern recognition that can be used to classify reflector characteristics in a feature-based ultrasonic inspection system, expanding on some of the author's ideas presented earlier.<sup>1</sup> Several sample problems are presented that utilize the feature-based methodology process.

Pattern recognition is not new. Many attempts have been made over the last three decades to advance the state of the art in flaw classification analysis by using techniques and concepts from pattern recognition. The new part of pattern recognition is associated with computer implementation and objectivity. Signal features, however, have been recognized for many years and have been used to characterize defect types,

particularly in steel weldments.<sup>2-5</sup> One of the most popular reflector classification techniques in welded structures is to examine total pulse duration of an echo as it is reflected from an area inside a weld. The fact is noted that porosities and slag inclusions produce very long pulse durations, whereas crack-type defects produce very short durations. As the trained and experienced ultrasonic operator moves the ultrasonic transducer over the area of concern, that is, by "cultivating the echo" and/or "peaking out" the ultrasonic transducer, the operator notices many things on the oscilloscope screen. As the ultrasonic transducer moves directly away from the flaw, amplitude changes from an echo dynamics viewpoint can be studied to learn something about the flaws in question. Magnitudes that remain fairly constant as the transducer is moved directly away from the flaw are associated with slag inclusions and porosities, whereas sharp drop-offs in amplitude are generally associated with crack- or critical-type defects. In addition to moving directly away from the flaw, it is possible to move the ultrasonic transducer in an arclike motion. When doing this, again the amplitude is noticed to remain approximately constant for spherical-type or smooth reflectors, porosity groups, and so on.

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On the other hand, moving an ultrasonic transducer in an arc-like motion around the reflector in question produces a very sharp change in magnitude if the reflector is indeed a crack. These observations are noted because of the phase variations of portions of the reflected ultrasonic energies as they return to the receiving transducer, planar defects appearing to be more specular in nature if the wave impingement angle is reasonably good, with more portions of the ultrasonic waveform returning in-phase as the portions are reflected from all areas of the defect. Concepts like this have been recognized by trained, experienced operators for years and have been utilized in their inspection schemes. Most inspection codes to date, though, are based on amplitude only, that of considering an equivalent flat bottom hole size and a certain percentage of the distance amplitude curve (DAC) with respect to the criticality of a defect. Trained operators use this pattern recognition knowledge to point out the areas of concern in weldments. Quite often, the flaw is looked at with several different angle probes, again to examine the ultrasonic reflector's response. Sometimes the defect is examined from both sides of the weldment to observe signal feature changes. The pattern recognition techniques that are being currently proposed make use of computers for implementation to promote reliability and objectivity. The features recognized by the experienced operator are extracted automatically by a computer and used in an algorithm that classifies that reflector as either critical or noncritical or as class 1 or 2.

Going beyond the classical techniques in ultrasonic nondestructive testing (NDT) that makes use of arrival time analysis and amplitude analysis, one can first consider signature techniques. A library-type effort called template matching or signature analysis in time domain was seen as an early pattern recognition effort. Generally, these techniques led to practical working rules, but unfortunately many exceptions to the rules were found. Additional signature techniques making use of a Fourier transform or frequency profile were then introduced.

Gericke<sup>6</sup> in 1963 suggested that a source of additional discriminating characteristics might be found in the frequency spectrum of the returned echo. He indicated that if a short pulse, rich in spectral content, were used, the size, nature, and shape of flaws could be more readily determined from the frequency domain. He also proposed a method involving the use of two widely separated frequencies for inspection. The change of the returned pulse shape from one frequency range to the other could possibly yield information concerning the defect's size, shape, and orientation characteristics.

Whaley and Cook<sup>7</sup> in 1970 also presented an article describing methods of ultrasonic frequency analysis. Shortly thereafter, Adler and Whaley,<sup>8</sup> in a joint venture, showed how multifrequency analysis might be used for flaw characterization when using the pulse-echo method of inspection. They could separate variously shaped reflectors in a water tank by examining the frequency signature. This early work made use of a spectrum analyzer, without phase information, for generating the frequency characteristics of the echoes.

The frequency signature technique was also used by Rose, Carson, and Leidel<sup>9</sup> for detecting damage in a composite structure. Comparisons of frequency signatures for indicating damage with radiographic techniques for composites were reported by Rose and Shelton.<sup>10</sup> A variety of additional signature techniques for ultrasonic examination was introduced by Mast and Rose.<sup>11</sup> This report utilizes the Hilbert transform, the Mellin transform, and many others that could be of value in ultrasonic testing (UT).

Many attempts have recently been made to understand the mathematics and physics of frequency signatures. Utilization of a frequency profile for measuring the thickness of thin layers was carried out by Rose and Meyer<sup>12</sup> in 1974. The relationship between spectral depression spacing and layer thickness is derived in the work. This concept can be extended to many different problems in UT, with the problem of adhesive bond inspection being directly related to the layered thickness concept.

Model analysis is also useful in pattern recognition by serving as a reminder that there is no substitute for good data acquisition that makes use of the physics of wave propagation. In a paper by Rose,<sup>13</sup> a 23 flaw sorting study is carried out that is based primarily on a mode conversion characteristic associated with sharp-edged defects. The conversion of longitudinal energy into shear-wave energy at the edge of the defect and resulting ultrasonic field characteristics made flaw classification fairly simple. This data acquisition procedure based on the physics of mode conversion, combined with techniques from pattern recognition, made flaw sorting possible.

Proceeding with a discussion of some techniques in advanced pattern recognition that make use of computer analysis, one encounters one of the first problems studied with adaptive learning methodology, flat bottom hole classification, reported by Mucciardi and Shankar<sup>14</sup> in 1975. An excellent index of performance was achieved for classifying variously sized flat bottom holes. Many of the techniques used by Mucciardi and Shankar were taken from some classical material on learning machines. See, for example, Nilsson<sup>15</sup> and Duda and Hart.<sup>16</sup> A variety of pattern recognition techniques was also presented by Rose, Niklas, and Mast<sup>17</sup> in 1976 and Rose<sup>13</sup> in 1977 for flaw sorting analysis. The adhesive bond problem was approached by Rose and Thomas<sup>18</sup> in 1978, where an index of performance of approximately 92 percent was achieved.

The topics presented so far describe historical developments and observations that have led to the development of current feature-based inspection philosophy. What follows is the methodology associated with a feature-based inspection program and a description of four sample problems that make use of a feature-based approach. The problems include adhesive bonding, weld inspection, stainless steel pipe inspection, and breast tissue examination.

## METHODOLOGY

The overall methodology employed in the development of a feature-based test system is outlined in the following paragraphs. The items discussed represent specific courses of action that have proved successful in several reflector classification programs. Although countless variations in features, algorithms, the quantification process, etc., could be considered, the items that are presented have produced a significant improvement in the sample problems considered in this paper.

The first step in a feature-based ultrasonic inspection process is to use a computer-controlled test bed. The acquisition of reliable ("high-quality") ultrasonic waveforms is necessary. These waveforms can be digitized, that is, decomposed into a discrete time sequence. A minicomputer accepts these sequences and performs certain mathematical operations on them, such as determining maximums and minimums, etc. This process is known as feature extraction.

Processing of the stored data utilizes several complex schemes or algorithms that search for innate groupings of the feature data. These data are ordered with respect to their effect in defining particular groupings. Upon completion of processing, the significant features are combined to develop a classification scheme.

Algorithm development then makes use of many techniques in pattern recognition, the goal being to establish some relationship between a classification mode and a number of important ultrasonic signal features.

The flow chart shown in Fig. 1 shows the principal components of a feature-based ultrasonic inspection development program.

In general, the reliability of an ultrasonic flaw detection system depends on two principal items: (1) the ability of separating flaw signals from noise and (2) the capability of separating class 1 signals from class 2 types of indications.

The first problem can be addressed by using special transducers in many cases, for example, by using dual probes, different frequencies, focused probes, etc. Signal processing, by

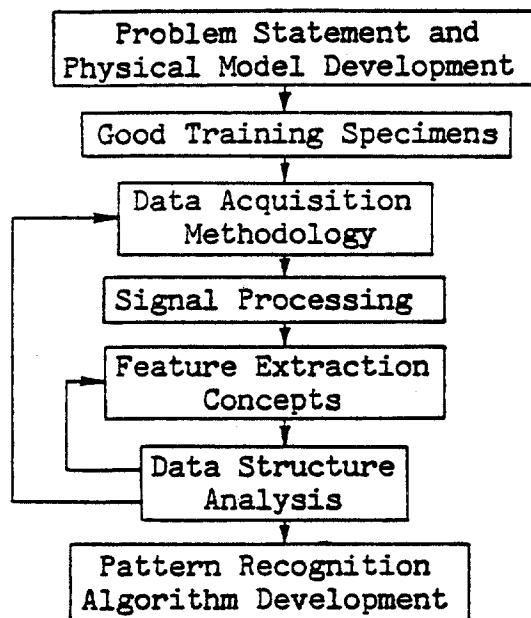


Figure 1—A feature-based ultrasonic inspection procedure.

way of signal averaging, spatial averaging, etc., can also be useful.

The second problem, that of separating class 1 indications from class 2 situations, has been reasonably addressed by establishing a feature-based pattern recognition decision system. Contained in the following paragraphs is an outline of some of the items considered in the development of a feature-based UT system. Eight sections are now described that summarize some of the thoughts and concepts that should be considered in any feature-based development and implementation program. These items include (1) criteria for feature selection, (2) the quantification process, (3) requirements imposed on search unit calibration, (4) selection of physical samples, (5) use of computer simulation, (6) physical implementation, (7) qualification, and (8) field usage.

### Criteria for Feature Selection

Features of an ultrasonic signal that are selected for further analysis and for their ability to differentiate class 1 reflectors from class 2 types of indications are usually physically based but can also be statistically based. Physically based features could include, for example, rise time, pulse duration, and fall time; these features give an abruptness measure of the reflector in question. In other words, cracklike reflectors could be more specular in nature compared with geometric-type indications, therefore producing shorter rise times, shorter pulse durations, and also shorter fall time values.<sup>19,20</sup> Other signal features could also be explored that, for example, would allow a look at the time domain features of rise time, pulse duration, and fall time and their relationship with angle of impingement to a reflector in question.

Features could also be taken from the frequency profile of an ultrasonic wave packet. For example, it might be convenient to look at a variety of power ratios calling the total area of the frequency curve from 1 to 2.5 MHz as unity, then examine partial powers (in the range of 1 to 1.5 MHz, also 1.5 to 2 MHz), and finally complete the spectrum from 2 to 2.5 MHz. It might be expected that cracklike indications would produce a more well-defined Gaussian-type power distribution compared to the larger variations that would come about from a set of geometric-type indications. The specular model concept, again, represents the physical basis for this observation. Features selected for study are based on both physics and actual experimental experience, thus the reason for selecting partial powers from 1 to 1.5 MHz or 0.9 to 1.6 MHz, one area perhaps

being less sensitive to noise, but both satisfying the physics of energy absorption ratios of high to low frequency, etc. Features are general, but specific thresholds and ranges must be determined from a variety of data collection experiences for optimum efficiency in feature determination for later classification analysis.

Features could also be taken from the transfer function domain. Features that could be examined from a statistical point of view could include such items as peakedness, skew characteristics, etc. Hundreds of features could be explored for their utility in discriminating class 1 from class 2 types of indications. Once the long list of features is established, detailed analysis must be carried out to select the features of primary concern. The use of probability density function curves (PDFs) is useful in this selection process so that the usefulness of one feature alone for discriminating one class from another could be examined.

Even though emphasis is placed on physically based features and on statistical features, the observations made by a trained operator are also used for providing insight into the feature selection process. For example, inspectors in the field have visually observed features of the ultrasonic waveforms by evaluating the video envelope of the reflected signal rather than a radio frequency (rf) ultrasonic waveform that is usually acquired in a research laboratory environment. In a computer-based system, use is made of similar features. As an example, in examining rise time, pulse duration, and fall time of the video envelope of the ultrasonic signal packet, other features that might be considered include multiple echoes, variations with distance of the ultrasonic packet waveform, and so on. Many of these observations, though, can be associated with either a physically based or a statistically based ultrasonic waveform feature.

Another interesting point worth noting in the feature selection process is related to the data collection program. The physics of wave propagation must be considered in the data collection process because features associated with beam scattering, mode conversion, etc., could be useful in reflector discrimination. A physical model of the problem being studied is useful. The data collection process, therefore, allows these variations in wave propagation and physics to occur so that the data collection process could be complete. This allows operators to use proper transducers and to explore reasonable features so that the quantification process and algorithm development scheme can take place. Four sample problems are discussed in this paper that review the physical models used and the subsequent feature selection and classification process.

### The Quantification Process

Once reasonable features are selected for analysis, it becomes necessary to establish an algorithm to decide which type of reflector produced a particular signal (a class 1 or a class 2 type of indication). One useful technique is to make use of a Fisher linear discriminant function, which includes a linear combination of the useful features.<sup>16,18</sup> As an example, it can be said that threshold value equals weight one times feature 1, plus weight two times feature 2, plus weight three times feature 3. The problem then becomes one of finding the proper weights in these linear functions and of establishing a reasonable threshold value so that classification can take place. Mathematical procedures are available to optimize weight and threshold selection for good algorithm performance. The Fisher linear discriminant is easy and simple to use, but it is only one of many that could be used to solve various classification problems. Good training specimens are necessary, ones with known class 1 and class 2 types of indication information. It might be noted that the quantification process can be improved by establishing an "uncertain" zone around the threshold. Signals that provide decision values that are within that zone would then call for a data retake procedure. Statistically, this significantly improves the decision capability. The quantification process is also improved by introducing decision averaging over

the reflector areas of interest.

Considering more details of the specific quantification process employed in a feature-based development program, one notices that PDF curves, like those shown in Fig. 2, are used in a number of ways. The potential value of a single feature can be determined. They can also be used to develop two-space scatter diagrams that are easy to analyze from a visual inspection point of view. Quite often, one feature is not sufficient for solving a classification problem. On the other hand, two features have shown great promise for signal classification. Obviously, if five features are examined, ten two-space scatter diagrams could be produced, each producing a different index of performance values. The best features from the PDF analysis can be used to study the most promising two-space diagrams. If results are still not acceptable, the PDF input with the best feature information can be used to extend the analysis into N-space, say, for example, with a Fisher linear discriminant technique. A two-space scatter diagram is presented in Fig. 3. A search for these class 1 and class 2 clusters is very easily carried out in two-dimensional space. As an alternative to cluster analysis, one might recognize in two-space a linear decision surface that seems to separate the data nicely into two classes. Selection of this line, of course, can vary the sensitivity and specificity of the pattern recognition algorithm selected for this study. Of ten two-space scatter diagrams that are possible in a five-feature study, one is shown in Fig. 3 for tutorial purposes. A retake philosophy could also be established that actually considers two parallel lines on the two-space scatter diagrams, with the interior region being called a retake zone, as shown in Fig. 3. Inspection has indicated that this procedure can usually produce a marked improvement in algorithm performance

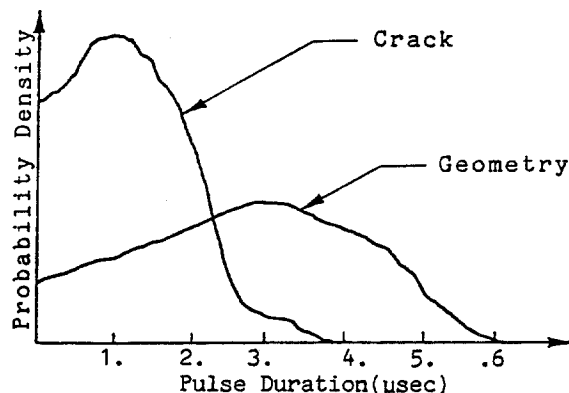


Figure 2—PDF curves showing pulse duration versus frequency of occurrence for cracks and geometries (304 stainless steel pipe inspection sample problem).

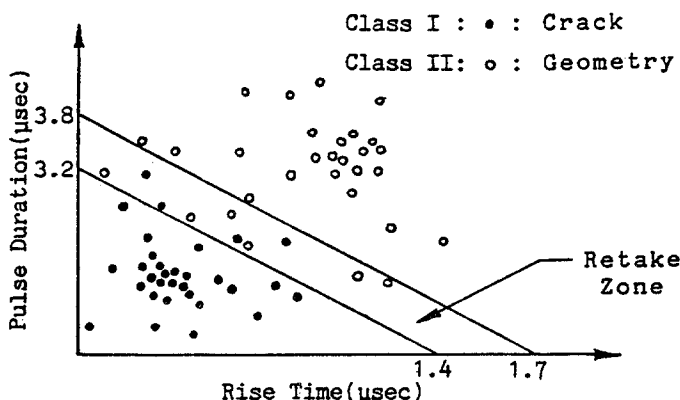


Figure 3—Two-space scatter diagram showing rise time versus pulse duration with a retake zone for improved performance (304 stainless steel pipe inspection sample problem).

because a data retake experiment usually forces the data points to fall farther away from the decision surface.

The algorithm being employed in several sample problems discussed in this paper makes use of a Fisher linear discriminant algorithm that expands beyond PDF curves and two-space scatter diagrams so that an n-dimensional feature space can be considered.

Threshold adjustment in an algorithm can also be used to emphasize either the economics or safety issue of a decision. Sensitivity is generally defined as the ability to find the number of class 1 reflectors in the total population of class 1 reflectors. Specificity is generally defined as the ability to find the number of class 2 reflectors in a total population of class 2 reflectors. False alarm is generally defined as the number of false critical calls divided by the total population of reflectors. Figure 4 illustrates the changes in sensitivity and specificity that could come about for a change in the threshold value in the algorithm.

#### Requirements Imposed on Search Unit Calibration

The algorithms that are developed to make a confirmation of either a class 1 or class 2 type of indication in the structure are strongly dependent on the ultrasonic transducer that is used in the study.

Unfortunately, a rather strict acceptance criterion is necessary for acquiring a transducer and pulser system that would perform well with a specific pattern recognition algorithm for reflector classification analysis. In particular, the ultrasonic wave packet features are critical. For this reason, calibration data are required from a known reflector that permits examination of the key features of a particular ultrasonic transducer. A series of studies should be conducted to show that these values must be within a mean value, plus or minus a certain percentage value, to guarantee good performance of the decision algorithm. These tolerances allow operators to use a large number of ultrasonic transducers and pulser-receiver systems for collecting the data and subsequently for making reliable decisions on the type of reflectors being analyzed. Transducer characterization is very important in this process because data acquired are compared with the reference signal to make reflector classification analysis possible.

Development of a transducer and system compensation procedure should be developed. Deconvolution procedures are available.<sup>21</sup> Algorithm modifications are also possible that permit the use of adjusted features that automatically compensate for pulser-receiver and transducer variations, provided key feature values of the test system do not vary by more than approximately 20 percent.

#### Selection of Physical Samples

The physical samples used in classification work must be

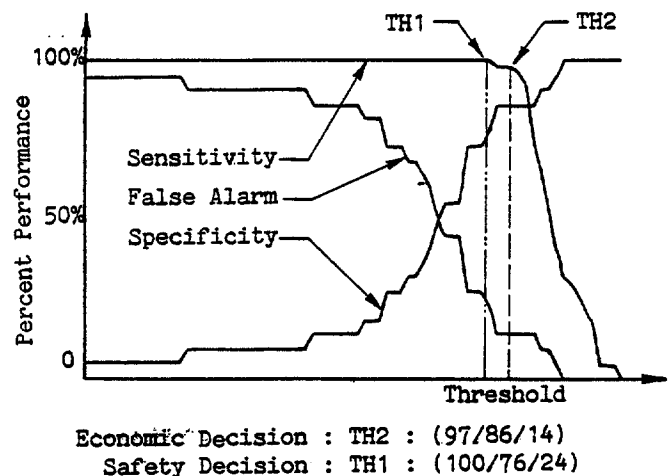


Figure 4—Threshold adjustment concept.

representative of the actual defects that occur in production or in service. It is desirable, therefore, to get as diverse a population of class 1 and class 2 types of structures as might be possible. This tedious and difficult work task is a necessary first step to any problem carried out in pattern recognition. The real test of performance is based on evaluating feature and algorithm performance on a variety of new test specimens with defects of interest.

### Use of Computer Simulation

In developing a feature-based system, a minicomputer test bed to acquire and develop algorithms is necessary. If developing an analog simulation, for example, a Hilbert transform to generate the waveform envelope may be used, which is then used for subsequent feature extraction. Many other filtering procedures—as an example, for extracting partial power features—can also mimic an analog circuit device.

### Physical Implementation

Development of a feature-based unit, utilizing all of the concepts outlined in this paper, incorporates many aspects of human engineering. It is possible to use standard procedures and codes to acquire data and then to further examine data sets of interest as reported by the ultrasonic technician. This system must not only be easy to use but also must be adaptable to a variety of ultrasonic transducer and pulser-receiver units as long as the system meets the system acceptance criterion, which shows up by way of display lights or a message on the instrument. Implementation must be made simple with good operation manuals and simplicity of operation in mind.

### Qualification

Earlier sections have described the necessity of transducer acceptance and the utility of physical samples. These items must also be considered when preparing an instrument for field usage. The instrument must pass certain tests on unknown test samples that are designed to give the technician a measure of confidence in the instrument.

### Field Usage

Assuming that the feature-based system does well in qualification, the question of actual field implementation arises. The instrument may serve as an assist device for decision making or as a single complete test unit itself. Feedback from field use will often improve the instrument's performance and human engineering design aspects, leading to a final test package.

## SAMPLE PROBLEMS

Four different reflector classification problems are now discussed that make use of a feature-based ultrasonic inspection program. Principal points of the discussion are summarized in Table 1.

### Adhesive Bond Inspection

The primary concern in an adhesive-bonding inspection program is directed toward the determination of interface quality. The cohesive problem can be addressed reasonably well with resonant techniques. Delaminations can be observed quite well with C-scan techniques. The adhesive problem, on the other hand, must be approached with a pulse-echo ultrasonic technique. Recent work carried out in adhesive bond inspection that utilizes a feature-based methodology is presented by Rose, et al.<sup>22</sup> A brief review of that work is presented briefly below.

First of all, the problem addressed is related to a two-class problem solution where class 1 is defined as the group of adhesive bonds with excellent interface quality. Class 2 situations are defined as the group of structures with poor interface quality, which comes about because of poor quality control and errors in surface preparation and application. These are adhesive bond structures that, from a traditional ultrasonic pulse-echo approach, appear similar from an amplitude viewpoint but still fail at loads and stress states that are much below the values considered in the design of the structure.

In a feature-based system, a physical model must first be developed that provides guidelines for data acquisition and for the establishment of a list of potentially useful signal features that could be used to develop an algorithm for separating class 1 structures from class 2 structures. The physical model considered in adhesive bonding analysis consisted of a local area discontinuity situation at the interface.<sup>23</sup> Theoretical considerations of this physical model suggest that the reflection factor of an ultrasonic wave as it impinges on this area of discontinuity would therefore vary and hence become a function of material properties across the interface, the area discontinuity percentage, and the thickness of the area of the discontinuity sections, in addition to the frequency components of the ultrasonic wave. Making use of physics in a qualitative sense, it is found that a frequency range of 10 to 15 MHz should be considered so that maximum sensitivity in two different feature sources could come about.<sup>23-24</sup> The feature sources considered were time domain amplitude ratios and the transfer function in frequency domain between the impinging ultrasonic waveform and the resulting echo from the adhesive bond. The specific features derived from these feature sources have been re-

TABLE 1 Sample Problem Feature-based Methodology Considerations.

	Adhesive Bond Inspection	Weld Inspection	Stainless Steel Piping Inspection	Breast Tissue Examination
Class 1 and Class 2	Excellent versus poor	Planar versus volumetric defects	IGSCC <sup>a</sup> versus geometric	Malignant versus benign
Physical Model	Local area discontinuities at an interface	A specular model	Multifaceted sparkling model	Low-pass frequency filter model
Frequency Range	10 to 15 MHz	2.25 to 5.0 MHz	1.5 MHz	3.5 MHz
Test Mode	Immersion, normal-beam broadband	Contact, shear-wave, int. bandwidth	Contact, dual-element shear-wave angle-beam, int. bandwidth	An immersion, normal-beam, broadband
Signal Processing	Spatial and temporal averaging	Temporal averaging	Spatial and temporal averaging	Spatial and temporal averaging
Feature Sources	Time domain amplitude ratios, transfer function	Video envelope in time domain	Video envelope in time domain	Fourier power spectrum
Features	Area ratio of a transfer function, amplitude ratios	Rise time, pulse duration, and fall time	Rise time, pulse duration, and fall time	Power spectrum absorption as a function of frequency
Algorithm	Two-space diagram, sorting tree	Linear discriminant	Linear discriminant	Linear discriminant
Reference Numbers	22	19	20	25

<sup>a</sup>IGSCC stands for "intergranular stress corrosion cracking."

ported<sup>22</sup> and resulted in an excellent index of performance of sensitivity, specificity, and false alarm rate. Spatial and temporal averaging were necessary.<sup>22</sup>

Features considered in the above-mentioned report<sup>22</sup> are illustrated in Figs. 5 and 6. The feature in Fig. 5 was used in a two-space scatter diagram of a log-weighted function of  $\alpha$  versus a surface integral of  $\alpha$ . The log-weighted feature gave more importance to a strong area of an adhesively bonded structure, whereas the surface integral function provided a spatial averaging procedure over an area of interest in the structure. Figure 6 illustrates the transfer function feature of A1/A2. To illustrate the methodology associated with algorithm development, the nature of the decision algorithm is depicted in Fig. 7.

The use of physics in the development of a feature-based ultrasonic test system for determining interfacial quality of an adhesive bond was carried out very successfully in a number of laboratory test cases.<sup>22</sup> It is anticipated that the technology transfer process from laboratory to field use could take place reasonably well because of the recent developments in scanning technology and microprocessor utilization. Good training test samples will be required to fine tune the variables associated with data collection, feature extraction, and algorithm development.

### Weld Inspection

A variety of problems in weld inspection could be defined where reflector classification analysis would be useful. First, consider a two-class problem where class 1 types of reflectors would be defined as a group of planar reflectors consisting of cracks and possibly lack of fusion areas along the weld line in

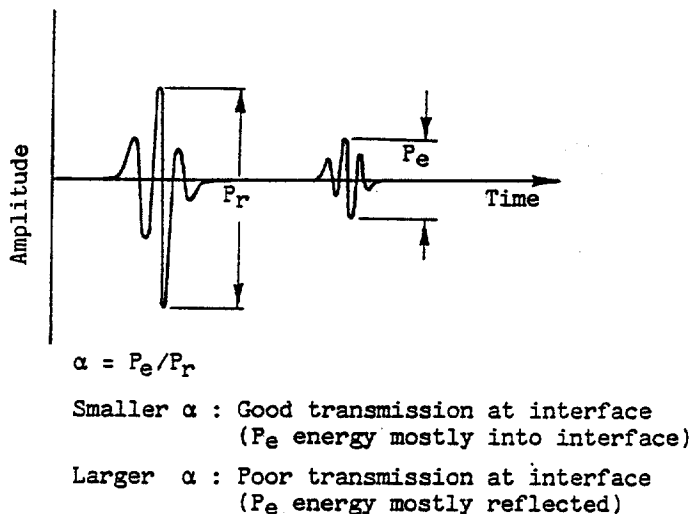


Figure 5—Definition and reasoning for peak-to-peak ratio feature,  $\alpha$ , for adhesive bond inspection.

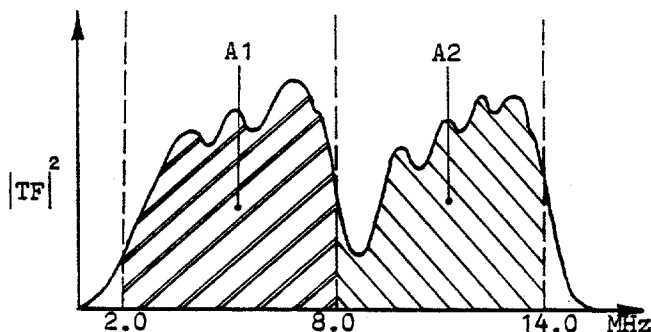


Figure 6—Transducer function feature A1/A2 used in adhesive bond inspection.

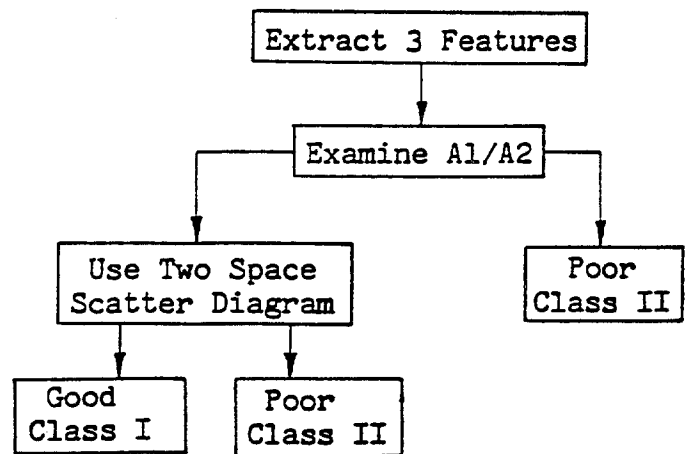


Figure 7—Sorting algorithm for bond quality assessment.

a weld structure. Also assume that class 2 types of reflectors would be that group of reflectors that are volumetric in nature, consisting possibly of porosity, porosity groups, slag inclusions, and a variety of geometric-type reflectors including crown-type and root-type reflectors.

Again, a physical model is required initially so that a suitable data acquisition and feature extraction program can be proposed. A specular model is proposed.<sup>19</sup> It is assumed that if normal incidence of an ultrasonic wave impinging on a reflector could be possible, then pulse-shape characteristics of the impinging ultrasonic waveform could be preserved. The reflection is not completely specular; however, if the reflector is several wavelengths in size, it can be assumed that the ultrasonic wave traveling from the reflector back to the ultrasonic transducer would contain very little pulse-shape variation in the component of the waveform being reflected from different points of the reflector. Thus, obvious features such as rise time, pulse duration, and fall time of the video envelope in time domain would change very little with respect to the incident ultrasonic waveform being sent from the ultrasonic transducer. On the other hand, reflections from volumetric-type reflectors would contain considerable interphase variation from one point of the reflector to another, thereby producing significant changes in the pulse-shape features. Rise time, pulse duration, and fall time would all increase in value. (Features considered in this study are illustrated in Fig. 8.)

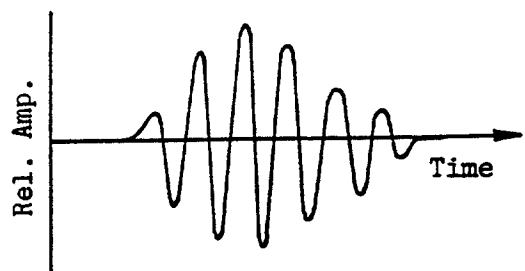
The data collection process would therefore call for angle selection of a shear-wave transducer to be selected so that impingement can be as normal as possible to the reflector of concern inside the weld structure. Obviously, some case history analysis is necessary so that the inspection program can seek out specific reflectors that are known to occur because of a specific fabrication process, in-service environment, or an anticipated stress state of the structure.

Because of the variations in planar-type reflectors and in volumetric-type reflectors from one test specimen to another, the qualitative use of physics permits the employment of the methodology discussed in this paper, that is, making use of PDFs and algorithm development based on desired sensitivity, specificity, and false alarm ratios.

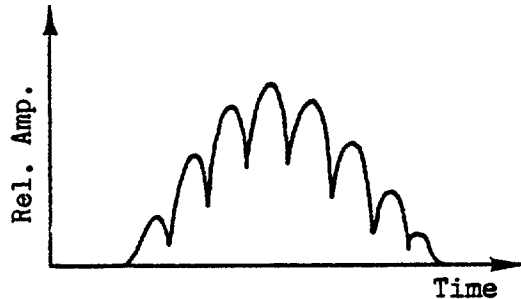
Successful studies employing a feature-based inspection concept have been reported.<sup>19</sup> A Fisher linear discriminant algorithm can be used. Excellent results were obtained providing sensitivity values greater than 90 percent, specificity values on the order of 90 percent, and false alarm values less than 10 percent.

### Stainless Steel Pipe Inspection

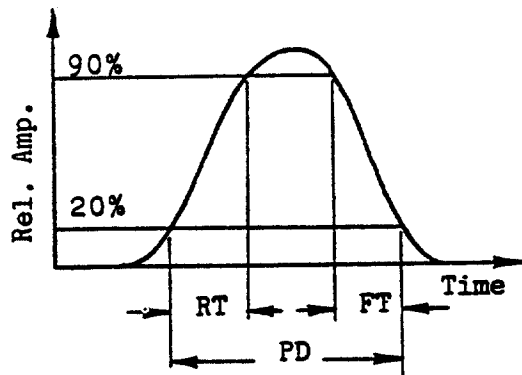
A problem of interest in the nuclear industry is related to the separation of cracklike reflectors in stainless steel piping from geometric-type indications. In this sample problem,<sup>20</sup> class



(a) Acquired RF Waveform



(b) Rectified Waveform



(c) Video Envelope and Feature Definition

$$Y1 = w_1 RT + w_2 PD + w_3 FT$$

Figure 8—Features used in weld inspection.

1 reflectors are defined as intergranular stress corrosion cracking (IGSCC) reflectors that appear in the heat-affected zone of a stainless steel pipe weld. Class 2 reflectors are defined as a group of geometric-type reflectors that could come from a root area as either suck back, drop through, or possibly from the weld crown or a counter bore on the inside of the pipe.

First of all, work that has been reported<sup>20</sup> indicates that a specially designed transducer would be necessary to achieve a reasonable signal-to-noise ratio because of the large grains in the stainless steel pipe materials. Accordingly, a dual-element angle-beam transducer was used that made use of a forward-scattering technique rather than a backscattering procedure.

Again, a physical model of the reflectors being considered is necessary so that the data collection and feature extraction can be initiated. The specular model can certainly be considered in this study, but because of the walking nature of IGSCC as it propagates along the grain boundaries, the model was found to have some limitation; a multifaceted sparkling model was therefore developed. The problem, data collection process, and angulation features are shown in Figs. 9 through 11. In this model, small angulations of an ultrasonic transducer as it rotates about a reflector in question would preserve pulse-shaped

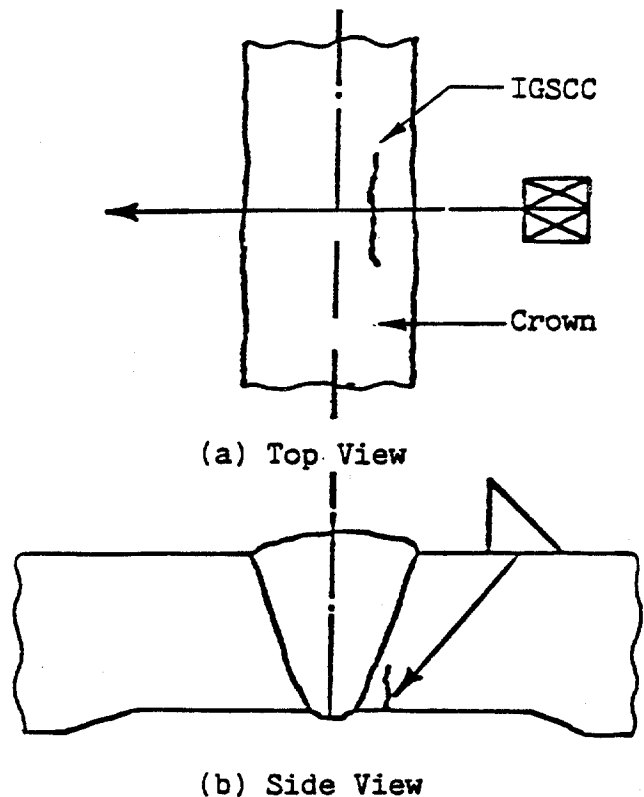


Figure 9—Radio frequency (rf) data acquisition along a single line of sight (peaking or cultivating the echo to a maximum).

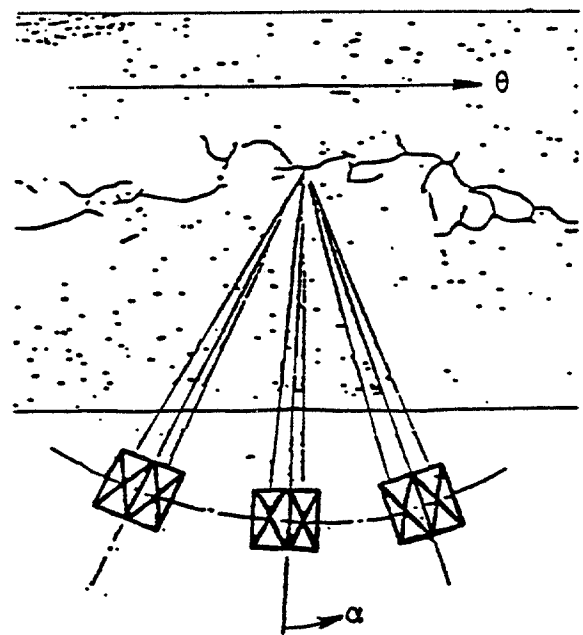


Figure 10—Proposed angulation data collection procedure (skew with a dual-element transducer).

features of rise time, pulse duration, and fall time. On the other hand, small angulations about a geometric-type reflector, because of severe phase variations, would produce severe discontinuities in the angulation profiles of rise time, pulse duration, and fall time. (Further discussion of the model is included in the above-mentioned report.<sup>20</sup>) With this in mind, a data collection protocol was established that made use of a Fisher linear discriminant function on the features of rise time, pulse



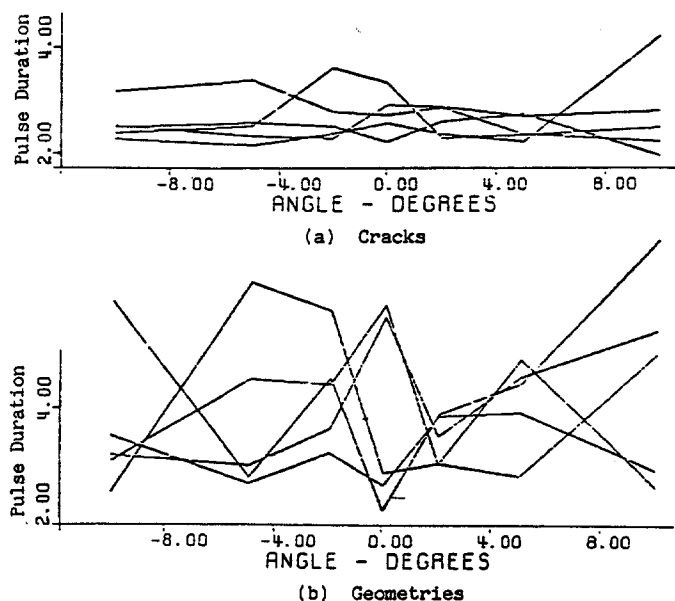


Figure 11—Pulse duration angulation profiles from 12 in. (305 mm) schd 100 304SS pipe (5 cracks, 5 geometries).

duration, and fall time in combination with a variety of angulation profile features. Excellent results were obtained.

### Breast Tissue Examination

A great deal of work is currently being initiated on the subject of tissue classification in medical ultrasound. For instance, a feasibility study on breast tissue examination was reported on in 1982.<sup>25</sup> Again, to make use of a feature-based examination philosophy, a physical model of the reflectors being considered in the human body was necessary. Even though B-scan imaging has progressed quite rapidly in developing excellent images of structures within the human body, the problem of separating malignant types of masses from benign structures has not yet adequately been demonstrated. Continuing on, class 1 reflectors can be defined as malignant reflectors, and class 2 reflectors can be defined as benign situations.

The first step in the feature-based examination program is associated with physical model development. A low-pass frequency filter model based on earlier observations and experiences was therefore established for malignant structures. In this case, absorption of ultrasonic energy is assumed to be greater at higher frequencies for malignant masses. The physics must be qualitative, however, because of severe variations in structural characteristics from one person to another and from one mass to another. A frequency range in the neighborhood of 3.5 MHz was considered as a compromise between penetration, resolution, and desired frequency from which absorption could be calculated. The feature source in this study<sup>25</sup> consisted of a Fourier power spectrum. Specific features were selected as area bins below the power spectrum curve over the available frequency range. Excellent results were obtained in this study.

The data collection process is illustrated in Fig. 12. An area of concern, inside the breast, can be located on a B-scan image so that the line of sight can be acquired from the area of interest. Spatial averaging was also used. Data collection is outlined in Fig. 13 with the specific features shown in Fig. 14.

### CONCLUDING REMARKS

The development of feature-based ultrasonic inspection systems is becoming a reality. A number of computer-controlled flaw detectors are commercially available that make implementation of a reflector classification algorithm relatively simple. Development of a special purpose analog feature-based

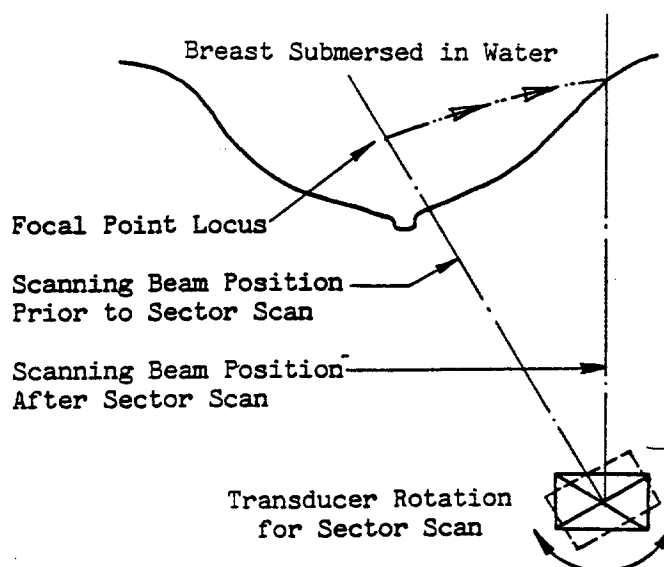


Figure 12—Data collection concept for breast examination.

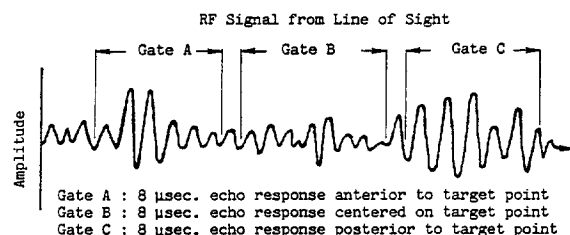


Figure 13—Gated region along a line of sight for breast tissue classification.

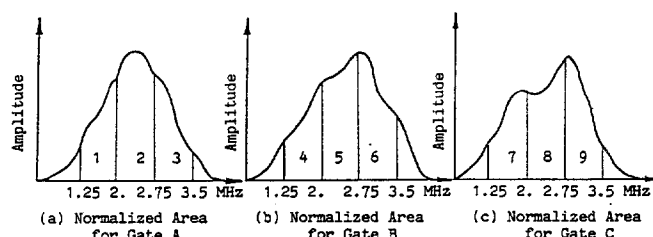


Figure 14—Features from the Fourier power spectrum used in breast tissue classification.

system can also be considered for certain applications.

Significant promise in solving the four sample problems considered in this paper has been made. Applications in adhesive bonding, weld inspection, piping inspection, and in tissue classification are therefore currently under way, with the technology transfer process from laboratory to field use proceeding smoothly. Applications in many other areas are also being considered that are employing the methodology discussed here concerning the feature-based ultrasonic inspection system.

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